

5. INTRODUCTION

The goal of this project is the development of a compact solid-state gamma camera specifically designed to image metabolically active tumors in the breast and axillary nodes with the highest possible detection efficiency and spatial resolution. The compact design (1) allows for a larger number of oblique views, (2) provides shorter imaging distances which results in improved spatial resolution and (3) reduces cost, which will make the instrument more widely available to the medical community. See Appendix 1, Figure 1 for a sketch of the imaging system, consisting of patient, camera, and readout electronics. See Appendix 1, Figure 2 for a sketch of the camera, consisting of the collimator, a 4 x 4 array of 64-pixel detector modules, the motherboard on which they are mounted, and the cable to the computer interface.

6. BODY OF THE PROGRESS REPORT

Tasks proposed for months 1-12:

- Purchase CsI(Tl) arrays and collimators (months 1-6)
- Fabricate silicon photodiode arrays (months 1-18)
- Fabricate custom integrated circuits containing charge amplifiers and WTA circuits (months 1-18)
- Assemble camera (collimator, crystal arrays, diode arrays, integrated circuit readout, flex strip output connections (months 9-24)

Tasks proposed for months 12-24:

- Fabricate custom integrated circuits containing charge amplifiers and WTA crystal identifier circuits (months 1-18)
- Assemble camera (collimator, crystal arrays, diode arrays, integrated circuit readout, flex strip output connections) (months 9-24)
- Interface camera to computer (months 18-24)
- Test system using calibration pulses and small ^{57}Co sources (months 20-24)

Tasks proposed for months 24-30:

- Measure intrinsic spatial resolution with and without scatter (months 24-30)
- Measure pulse height resolution with and without scatter (months 24-30)
- Measure planar sensitivity and count rate performance (months 28-36)
- Acquire images of isotope distributions using standard plastic phantoms (months 28-36)

Collimators

Based on our computer simulations [1], we have identified and acquired three collimator designs that will work well for breast cancer imaging. All have parallel

hexagonal channels with lead septa and cover an area $10 \times 10 \text{ cm}^2$ (more than sufficient to cover a plane of $16 \times 24 \times 24 \text{ mm}^2$ detector modules). All designs have 1.5 mm diameter holes and a septal thickness of 0.25 mm but vary in length: 23.5 mm (all purpose), 16.5 mm (high sensitivity), and 13.0 mm (ultra high sensitivity).

CsI(Tl) Crystal Arrays

Two CsI(Tl) $12 \times 20 \text{ cm}^2$ crystal arrays with a depth of 5 mm and optically-isolated $3.0 \times 3.0 \text{ mm}^2$ pixels were acquired. These were cut into 32 smaller 8×8 pixel arrays consisting of 64 pixels each. The average dimensions on these smaller arrays is $24.2 \times 24.2 \text{ mm}^2$.

Silicon Photodiode Arrays

We have successfully fabricated, diced, tested, and passivated 64-pixel (8×8 element) silicon PIN photodiode arrays (Appendix 1, Figure 3) [2]. These arrays are larger versions of the 12-pixel (3×4 element) arrays we had previously developed [3]. The new arrays maintain the same $3.0 \times 3.0 \text{ mm}^2$ pixel size and per-pixel capacitance of about 2 pF.

The 34 arrays diced from the 5 most promising silicon wafers provided a total of 2176 pixels with a 98.5% yield of "good" pixels (good being defined as $<100 \text{ pA}$ leakage current at room temperature and 50 V bias). These 2143 good pixels demonstrate an extremely low leakage current of $28 \pm 7 \text{ pA}$ (average \pm standard deviation) at room temperature and 50 V bias, about an order of magnitude better than the best 64-pixel arrays that are commercially available. These data are summarized in the histogram presented in Figure 1. We now have in our possession about 25 arrays whose performance makes them excellent candidates for the final 16-module camera.

Photodiode quantum efficiency at the 540 nm emission wavelength of CsI(Tl) is approximately 80%.

Custom Integrated Circuit Readout Chip

We developed a custom integrated circuit chip containing 64 low-noise charge amplifiers and pulse shapers, a 64-channel winner-take-all (WTA) crystal identifier circuit, address electronics, and computer control of both the shaping time and gain of the 64 individual amplifiers [4]. Based on testing and experimentation with this version of the chip, we had refined the design of both the low-noise charge amplifiers/pulse shapers and the WTA crystal identifier. This culminated in two new 16-channel prototype ICs (one for the amplifiers and one for the WTA) which were then thoroughly tested and debugged.

Based on those results, we have completed our design of the final version of the 64-channel custom readout IC. This IC incorporates both an improved array of 64 charge amplifiers/pulse shapers and an improved 64-input WTA circuit. (See Appendix 1, Figure 4.) The IC has been successfully fabricated, diced from its wafers, had its backside coated with gold, and been wirebonded to our custom IC test boards. The IC

meets performance expectations as follows: (1) power consumption is nominal, (2) rise and fall times can be externally adjusted, (3) the gain of each pre-amplifier can be externally adjusted, (4) the photodiode dark current compensation in each pre-amplifier can be externally adjusted, (5) qualitatively electronic noise looks acceptable, (6) the WTA circuitry correctly outputs the analog signal with the greatest amplitude, (7) the WTA circuitry produces the correct digital address for the channel with the largest analog signal, (8) the operational mode and noise-suppression threshold of the WTA can be externally controlled, and (9) the IC only responds to commands containing the correct identifier sequence (thus allowing multiple ICs on the same bus to be controlled separately). (See Appendix 1, Figure 5.)

Detector Module

See Appendix 1, Figure 6 for a photograph of a complete detector module, consisting of an 8 x 8 array of 3 mm x 3 mm CsI(Tl) crystals 5 mm deep, the low-noise silicon photodiode array, the ceramic mounting board, and the custom integrated circuit readout chip, and the emf shield. Appendix 1, Figure 7 shows the individual components.

The multilayer ceramic circuit boards host the custom IC readout and control lines and as well as bypass capacitors, a metal cover to protect and EM shield the IC, and connectors for plugging an individual module into the motherboard.

The steps that must be performed to complete an individual detector module are as follows:

- 1 The custom readout IC is mounted onto the ceramic board.
- 2 Wirebonds are made between the ceramic board and the IC.
- 3 A printed circuit board is glued to the ceramic board.
- 4 Wirebonds are made from the IC pads to bonding pads on the printed circuit board.
- 5 The photodiode array is attached to the ceramic using conductive epoxy for electrical connection.
- 6 Underfill is applied between the photodiode array and the ceramic board to minimize the stress on the conductive epoxy bond.
- 7 The CsI(Tl) scintillator array is attached to the photodiode array using optically-transparent epoxy.

Steps (1) to (4) are out-sourced to an assembly company. We have been doing steps (5) to (7) in our lab. Step (5) require precision alignment and careful dispensing of the conductive epoxy. We are in the process of evaluating out-sourcing steps (5) to (6) to another assembly company.

Motherboard

See Appendix 1, Figure 8 for a photograph of the printed circuit motherboard on which a 4 x 4 array of detector modules can be mounted. This motherboard also contains resistor networks, peak detect hardware, and electronically-adjustable potentiometers. Appendix 1 Figure 9 shows the readout timing and peak detect circuitry and Appendix 1, Figure 10 shows the overall readout architecture. Appendix 1, Figure 11 shows the motherboard timing diagram.

The motherboard employs a custom winner-take-all (WTA) IC to identify the module which has the largest analog output in any given event. The peak of the signal is found using a peak detect circuitry and subsequently sent to an ADC on the data acquisition card. The motherboard also enables the correct output address bits that identify the pixel that generated the “winner” signal.

We have fabricated 4 motherboards for the gamma camera. Each is capable of imaging with a maximum of 16 individual 64-pixel imaging modules resulting in a 1024-pixel camera covering an area of 9.6 cm x 9.6 cm.

Imaging Tests

The software for the data acquisition and calibration of the camera have been implemented and we have successfully demonstrated the camera’s capability and performance using a single imaging module excited with a 122 keV ^{57}Co point source (2.7 mm in diameter). See Appendix 1, Figure 12 for pulse height spectra from individual crystals, and Appendix 1, Figure 13 for the first images of a point source. The average energy resolution of the imaging module is about 17.4% fwhm for 140 keV gammas.

7. KEY RESEARCH ACCOMPLISHMENTS

- Arrays of 64 low-noise silicon photodiodes were fabricated with a yield per photodiode of 99% and an average leakage current in good elements of only 22 pA.
- We have developed a functional 64-input custom integrated readout circuit chip.
- Monte Carlo simulation software was developed and used to optimize the final camera design. High sensitivity hexagonal hole collimators and $3.0 \times 3.0 \text{ mm}^2$ silicon photodiode/CsI(Tl) scintillator pixels were shown to be wise design choices, while cooling of the electronics in order to lower noise proves unnecessary.
- Five high purity silicon wafers were fabricated and diced to produce 34 64-pixel photodiode arrays with a 98.5% yield of good pixels.
- Fabrication of the custom 64-channel integrated circuit readout chip was completed and testing shows that all functions are operational.
- Assembly procedures for the detector modules were developed, including gluing custom circuit boards together, mounting and wirebonding the integrated circuit, mounting the photodiode array, protecting the photodiode array with underfill epoxy, making additional wirebonds between the circuit boards and the photodiode array, and optically bonding the CsI(Tl) scintillator array to the photodiode array.

- Three printed circuit boards were designed and fabricated: (1) a test board for the custom integrated circuit (IC), (2) a ceramic board for mounting the photodiode array and hosting the IC fan in, and (3) a multilayer board for routing the IC output and control lines.
- We have completed construction of a compact gamma camera, consisting of 64 CsI(Tl) crystals, an array of 64 low-noise silicon photodiodes, and our custom readout integrated circuit. The first image of a point source was taken.

8. REPORTABLE OUTCOMES

G. J. Gruber, W. W. Moses, S. E. Derenzo, et al., “A discrete scintillation camera using silicon photodiode readout of CsI(Tl) crystals,” *IEEE Trans. Nucl. Sci.*, vol. NS-45, pp. 1063–1068, 1998.

N.W. Wang, G. Conti, S.E. Holland, N.P. Palaio, G.J. Gruber, and W.W. Moses, “Improved photosensitive contact for back-illuminated silicon photodiode arrays,” presented at the 1998 IEEE Nuclear Science Symposium and submitted to *IEEE Trans. Nucl. Sci.*

S. E. Holland, N. W. Wang, and W. W. Moses, “Development of low noise, back-side illuminated silicon photodiode arrays,” *IEEE Trans. Nucl. Sci.*, vol. NS-44, pp. 443–447, 1997.

Gruber GJ, Moses WW and Derenzo SE. Monte Carlo simulation of breast tumor imaging properties with compact, discrete gamma cameras. *IEEE Trans. Nucl. Sci.* 1999; NS-46:2119-2123.

G. J. Gruber, W. S. Choong, W. W. Moses, S. E. Derenzo, S. E. Holland, M. Pedrali-Noy, B. Krieger, E. Mandelli, G. Meddeler and N. W. Wang, “A compact 64-pixel CsI(Tl)/Si PIN photodiode imaging module with IC readout,” *IEEE Trans. Nucl. Sci.*, (submitted for publication), 2001.

Pedrali-Noy M, Gruber GJ, Krieger B, Mandelli E, Meddeler G, Moses WW and Rosso V. PETRIC—A Positron Emission Tomography Readout IC. *IEEE Trans. Nucl. Sci.* 2001 (in press).

9. CONCLUSIONS

We have developed or purchased final versions of all major components of the proposed compact solid-state gamma camera: collimators, CsI(Tl) scintillator arrays, special low-noise silicon photodiode arrays, and custom integrated circuit readout chips. Monte Carlo simulations have helped optimize the final camera design, supporting the use of high-sensitivity hexagonal hole collimators and $3.0 \times 3.0 \text{ mm}^2$ pixels while demonstrating that cooling the electronics is not necessary [1].

A complete single module gamma camera was fabricated and an initial image was taken. The energy resolution of 17.4% fwhm for 140 keV gamma rays can be improved because we measured 10.7 % fwhm using a preliminary 3 x 4 array.

Based on results to date, it appears that our compact camera design will yield very similar performance to traditional SPECT cameras. However, for the application of breast and axillary node imaging, our compact design will have the advantages of: (1) more potential imaging angles, (2) shorter imaging distances and hence higher image quality, and (3) lower cost, making the camera more readily available. Once completed, the new camera may help make scintimammography a valuable complement to traditional breast cancer screening and diagnostic techniques.

10. REFERENCES

- [1] G. J. Gruber, W. W. Moses and S. E. Derenzo, "Monte Carlo simulation of breast tumor imaging properties with compact, discrete gamma cameras," *IEEE Trans. Nucl. Sci.*, vol. NS-46, pp. 2119-2123, 1999.
- [2] S. E. Holland, N. W. Wang and W. W. Moses, "Development of low noise, back-side illuminated silicon photodiode arrays," *IEEE Trans. Nucl. Sci.*, vol. NS-44, pp. 443-447, 1997.
- [3] G. J. Gruber, W. W. Moses, S. E. Derenzo, et al., "A discrete scintillation camera using silicon photodiode readout of CsI(Tl) crystals for breast cancer imaging," *IEEE Trans. Nucl. Sci.*, vol. NS-45, pp. 1063-1068, 1998.
- [4] M. Pedrali-Noy, G. J. Gruber, B. Krieger, et al., "PETRIC - a positron emission tomography readout IC," *IEEE Trans. Nucl. Sci.*, vol. NS-48, pp. (in press), 2001.

11. APPENDICES

Appendix 1: Figures referenced in the body of the text

Appendix 2: Preprint of G. J. Gruber, W. S. Choong, W. W. Moses, S. E. Derenzo, S. E. Holland, M. Pedrali-Noy, B. Krieger, E. Mandelli, G. Meddeler and N. W. Wang, "A compact 64-pixel CsI(Tl)/Si PIN photodiode imaging module with IC readout," *IEEE Trans. Nucl. Sci.*, (submitted for publication), 2001.

Appendix 2 DAMD17-98-1-8302 Derenzo